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Water use optimisation based on the concept of Partial Rootzone Drying

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Abstract Partial Rootzone Drying (PRD) is the creation of simultaneous wet and dry (or drying) areas within the root zone. Only part of the root zone is irrigated and kept moist at any one time. This new irrigation strategy allows the exploitation of drought-induced abscisic acid (ABA) based root to stomata signaling system to water saving. In this research, the PRD technique is examined and simulated for wheat and maize crops in the Mashtul Pilot Area (MPA), Egypt using Saltmed model. The technique causes the stimulation of physiological responses which are normally associated with water stress and this result in a significant reduction in water use through the production of chemical signals in drying roots. The results confirmed an increase in irrigation water productivity using PRD comparing with conventional flood irrigation. The research highly recommends applying the PRD method in new reclaimed areas in Egypt to save water and improve crop quality.

1. Introduction

Irrigation requirements are sometimes estimated from environmental data (pan evaporation, soil moisture reserves and rainfall) and crop factors. Crop factors are multipliers which reflect the water requirement of a particular crop at different times of the year and depend on variables such as canopy area and stage of growth. They can vary by a factor of five and the success of this method of determining irrigation input is very much dependent on the use of realistic crop factors. In determining these factors, little thought is given to internal physiological changes in the plants which may substantially influence their efficiency of water use in the short term. For example, it has been known for a long time that water deficits will induce changes in the gas exchange characteristics of a plant which result in reduced water loss. Such a decrease in water use would obviously be an advantage if it could be achieved without detriment to the crop or any other aspect of crop performance [1]. However, to get the plant to exhibit these changed characteristics, it would normally be necessary to induce a degree of water deficit. This may be difficult to achieve in a conditions way and furthermore, the plant will recover over a period of time, making repeat water deficit events necessary for a sustained effect. This may be possible, but difficult to achieve in practice, and it is known that sustained water deficits usually result in a reduction in fruit yield. Ideally, it would be desirable to separate the positive effects of water deficits (improved water productivity and reduced allocation

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of resources to vegetative growth in comparison to fruit growth) from the negative effects such as reduced crop yield.

PRD, as the name suggests, is the creation of simultaneous wet and dry (or drying) areas within the root zone (Fig. 1). Only part of the root zone is irrigated and kept moist at any one time. PRD is implemented by irrigating one side of the plant row and allowing the other side to dry out. The irrigations are then alternated to the dry side after a set period of time and then back and forth thereafter the same period of time. If only part of the root system is dried and the remaining roots are kept well watered, chemical signals produced in the drying roots will reduce stomatal aperture. At the same time the fully hydrated roots maintain a favorable water status throughout the aerial parts of the plant. In other words, it is possible to separate the biochemical responses to water stress from the physical effects of reduced water availability. In addition to reduced stomatal conductance, it is noted that shoot extension is also inhibited. A surprising finding is that the effect is temporary, and despite the fact that part of the root system remained dry, stomatal conductance, photosynthesis and growth returned to pre-treatment levels within a few weeks [2,3].

Armed with knowledge about the transient nature of the effect and the likely role of abscisic acid (ABA) [4], it is possible to devise irrigation schedules to maximise the production of ABA and hence its inhibitory effects on transpiration and growth. In practice, this means applying water to one side of the plant for about two weeks and then changing to the other side. During the two week irrigation cycle it is important that water is supplied with sufficient frequency to the wet side to prevent excessive soil drying and to meet the needs of the whole plant. If all of the plant's roots become dry, a water deficit will be induced and this may impact negatively on crop yield. For example, in grapevines subjected to PRD, there is a consistent reduction in vegetative growth as measured by pruning weight. Another measure of canopy density is the amount of light reaching the bunch zone and this figure is consistently higher in PRD than in control vines. It has been a consistent feature of all trials that there was no significant reduction in yield due to PRD treatment even though irrigation amount is halved. As a result, water productivity is effectively doubled in response to PRD. The aim of this research is to examine and simulate novel irrigation method (Partial Rootzone Drying, PRD), which would stimulate the endogenous stress response mechanisms of wheat and maize crops in the Mashtul Pilot Area (MPA), Egypt using Saltmed model so that vigour is reduced and the efficiency of water use is enhanced [5]. This is to be achieved by the manipulation of the hydration status of parts of a crop's roots could be used to control vegetative vigour without detrimental effects on canopy water relations. In this paper, the PRD technique is researched for wheat as a winter crop and maize as a summer crop in Egypt. The technique causes the stimulation of physiological responses which are normally associated with water stress and this result in a significant reduction in water use through the production of chemical signals in drying roots. In addition, the research provides low cost irrigation techniques at farmers' level, monitor performance of the new techniques, and assessing the feasibility of implementation.

2. Implementation of PRD

There are several ways to implement PRD. In Australia where the technique was developed, vineyards have shallow soils and effective separation of the root system was achieved by drip irrigating the area between pairs of vines down the row while the areas between the vines in each pair were allowed to dry. When the rate of soil drying in the non-irrigated areas slowed or stopped, these areas were then irrigated on a normal schedule while the previously irrigated areas were allowed to dry. Switching the irrigated versus non-irrigated areas was done to maintain the beneficial levels of cytokinins and ABA. The first PDR irrigation systems installed consisted of two drip lines per row, each corresponding to an irrigation zone. Currently on the market are double, fused drip tapes that ease

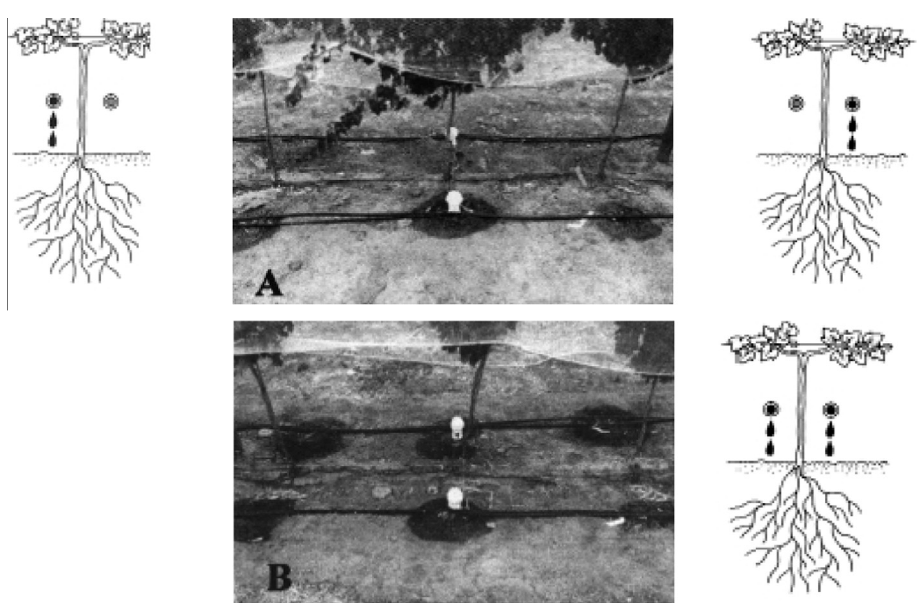

Figure 1 Partial Rootzone Drying irrigation system (A) and irrigation application (B) [1].

installation and keep each zone's emitters properly separated [6]. On deep or fine-textured soils where vines have extended root systems, the configuration of wet and dry zones between and within pairs of vines in the planted row may not be effective for splitting vine root systems. Root systems can extend well into the space between planted rows and beyond neighbouring vines within the row. An effective PRD drip system developed for use in this type of vineyard has three zones: one in the planted rows, another halfway between every second planted row, and the third halfway between the remaining planted rows. The three zones are irrigated one at a time. Growers should watch for signs of significant water stress and adjust the frequency of irrigations and switchover events to avoid levels of stress that lead to reduced vine performance. In vineyards with deeprooted vines on rich, fine-textured soils, it may be difficult to achieve an effective zone of dry soil. It may be worthwhile to first try PRD on a small area to observe whether there are benefits in comparison with full irrigation application. In this research, the PRD technique is examined and simulated for wheat and maize crops in the Mashtul Pilot Area (MPA), Egypt.

The water holding capacity of the soil in the vine rootzone is stated as Readily Available Water (RAW). The RAW holding capacity of the soil is the amount of water required to take the soil from the ''refill point'' (the stage at which soil moisture is low enough to slow vine growth) to ''field capacity'' (the point at which the soil can't hold any more water). Water applied which exceeds the ''field capacity'' will not be used by the vines, is wasted and can lead to increased drainage water. The drying and rewetting cycle by PRD induced new roots and this may make the nitrate in soil zone more available for the plants [1,7,8] and reduce the nitrate leaching to subsurface drainage water and improve the leached water quality from soil [9,10].

3. Mashtul Pilot Area as a case study

The field work was carried out in the Mashtul Pilot Area (MPA). MPA was constructed in 1980 in South-Eastern part of the Nile Delta [11]. It is situated 90 km northeast of Cairo in a rather flat area, as shown in Fig. 2. The area is approximately 260 feddans (feddan = 4200 m^2). Table 1 showed Irrigation schedule & amount and crop productivity in the Mashtul Pilot Area, 2005. The layout and design of this pilot area were already planned by the Drainage Research Institute (DRI) of the National Water Research Center (NWRC), as shown in Fig. 2. The southern and western boundaries are formed by the Mahmoudia Drain and its branch; the northern and eastern are bound by tertiary irrigation canals. It is characterized by a deep clay top layer and a sandy aquifer. The clay layer, which is approximately 6.0 m thick, contains about 35% silt and 65% clay. Irrigation water is delivered by gravity to the tertiary canals and lifted approximately 0.5 m to field level by pumps.

The area is drained through a subsurface drainage system that consists of parallel PVC lateral drains, which discharge into buried concrete collector drains through a manhole. The area was divided into eighteen drainage units with different drain depths and spacing. The units were cultivated with a single crop for each unit during each cropping season. Berseem (Egyptian clover) and wheat were cultivated as winter crops and cotton, rice, and maize as summer crops [12].

4. Method and materials

The SALTMED model [13,14], which was designed to be, generic, physically based, friendly to use and to include a number of physical processes acting simultaneously under field conditions was evaluated in experimental work. The model under all irrigation systems incorporates: evapotranspiration, plant water uptake, water and solute transport and crop yield and biomass production based on a relationship between water uptake and biomass. The water balance model is formulated for unsaturated condition. This condition can be conceptualized as four boxes in which the water content fluctuates over time. The model traces the portion of the irrigation water evapotranspired and the portion infiltrated through each layer and finally recharges the groundwater. The dynamics of water table and groundwater intrusion to the root zone are also represented. The water flow in soils was described mathematically by the well-known Richard's equation. It is a partial non-linear differential equation, partial in time and space. It is based on two soil physical principles: Darcy's law and mass continuity. The vertical transient-state flow water in a stable and uniform segment of the root zone can be described by a Richard's type equation. The solute movement is simulated using the convection–dispersion equation. The convection flux generally causes hydrodynamic dispersion too, an effect that depends on the microscopic non-uniformity of flow velocity in the various pores. Thus, a sharp boundary between two miscible solutions becomes increasingly diffuse about the mean position of the front. For such a case, the diffusion coefficient has been found by Bresler [15] to depend linearly on the average flow velocity.

Solving the water and solute transport equations requires two soil water relations, namely the soil water content–water potential relation and the soil water potential–hydraulic conductivity relation. They were taken according to Van Genuchten [16]. Values of several coefficients of van Genuchten equation such as ''n'', ''m'' constants were calculated based on the relationship between ''n'', ''m'' and the pore size distribution index. Bubbling pressure, soil water content at saturation, field capacity and wilting point, and saturated hydraulic conductivity were given in data base for different soil types and can be edited by users should filed data become available. In the one dimensional PRD model used for furrow irrigation, the calculation is carried out on three columns each of which has 1 m width and 2 m depth. The left and right columns are acting as boundary conditions to the middle column. The result of the middle column is the considered one. A detailed description of each functional relationship is given by Ragab et al. [17]. The Standard Flood Irrigation (STD) treatment was used to calibrate the Saltmed model for wheat crop in winter season and maize crop in summer season, 2005. After the calibration, the model was used to examine and simulate the PRD technique in MPA for the same crops.

5. Results and discussion

In two experimental fields cultivated with wheat and maize (Figs. 3 and 4), irrigation management was applied by using regulated deficit irrigation and subsequent trial including simulating PRD. The soil profile was divided into four layers: 0–30 cm; 30–60 cm; 60–90 cm and 90–120 cm. The SALTMED model was calibrated based on the measurements of the soil

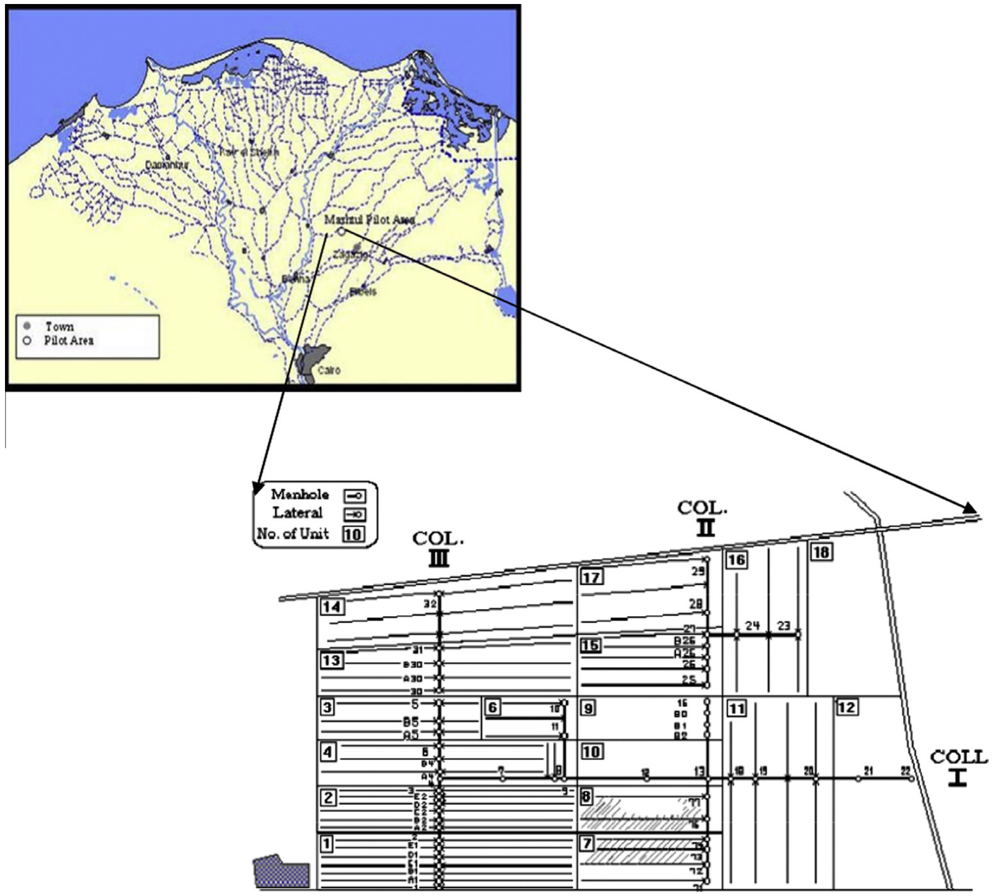

Figure 2 Layout of Mashtul Pilot Area in the Nile Delta.

Table 1 Irrigation schedule & amount and crop productivity in the Mashtul Pilot Area, 2005.

Crop	Irrigation schedule	No. of irrigations	Irrigation applied m^3 $feddan^{-1}$	Crop Productivity kg $feddan^{-1}$
Wheat	40–60 days after first irrigation then every 30 days	3	1500–1900	5088
Maize	Every 20 days	6	2000–2700	4233

moisture changes in the soil layers. In this study, the following statistical criteria were used to evaluate the performance of the model in simulating the soil moisture:

- Relative Root Mean Square Error (RRMSE).
- Mean Absolute Error (MAE).
- Coefficient of Determination (CD).
- Model Efficiency (EF).
- Coefficient of Residual Mass (CRM).
- Goodness of Fit (R^2).

The characteristic of the different statistical criteria is given in Table 2. The statistical analysis between simulated results and measured data, as shown in Table 3 for wheat and maize, revealed that the model is able to predict sufficiently accurate the measured soil moisture in the soil profile.

In the 2005 growing winter season for wheat and summer season for maize, PRD was modeled in MPA on a clay soil. The results confirmed an increase in apparent irrigation water productivity when compared with conventional flood irrigation. In this trial, there were three irrigation cycles during the winter season and six cycles during the summer season, and water was carefully applied and modeled in two ways, as follows: Standard Flood Irrigation (STD) where the entire section was flooded and Partial Rootzone Drying (PRD), where only one side of each crop line received water. The results indicated that the measured productivity of wheat and maize using STD was 5088 kg/fed and 4233 kg/fed in winter and summer season, 2005 respectively. The STD measured data were used to calibrate the Saltmed model, after the calibration, the Saltmed model was used to simulate the crop yield and the water productivity of the PRD treatment.

The model performance evaluation was based on comparing measured with modeled crop yield and water productivity in MPA maintained under STD treatment using indexes that are calculated on the basis of the square of modeling errors, the coefficient of determination (R^2; [18]). The evaluation results indicated that there is a good agreement between the

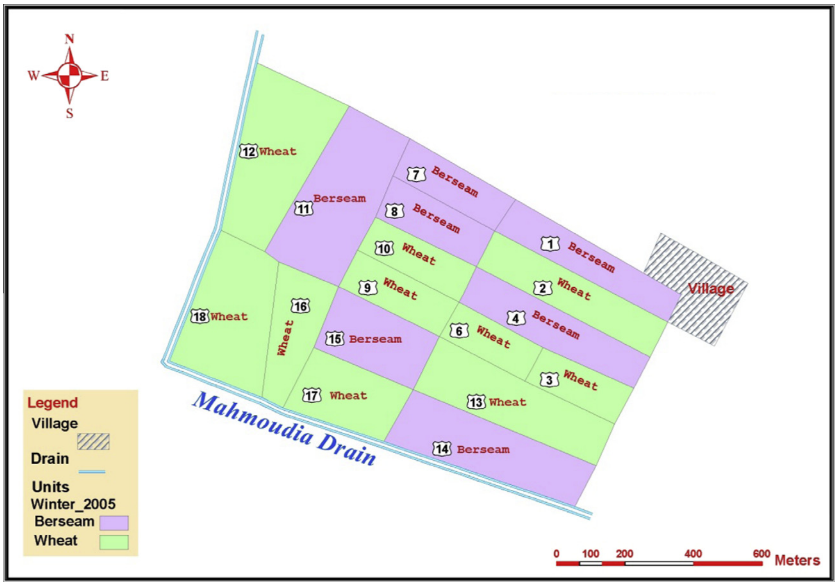

Figure 3 Crop pattern in Mashtul Pilot Area, 2005 (winter season).

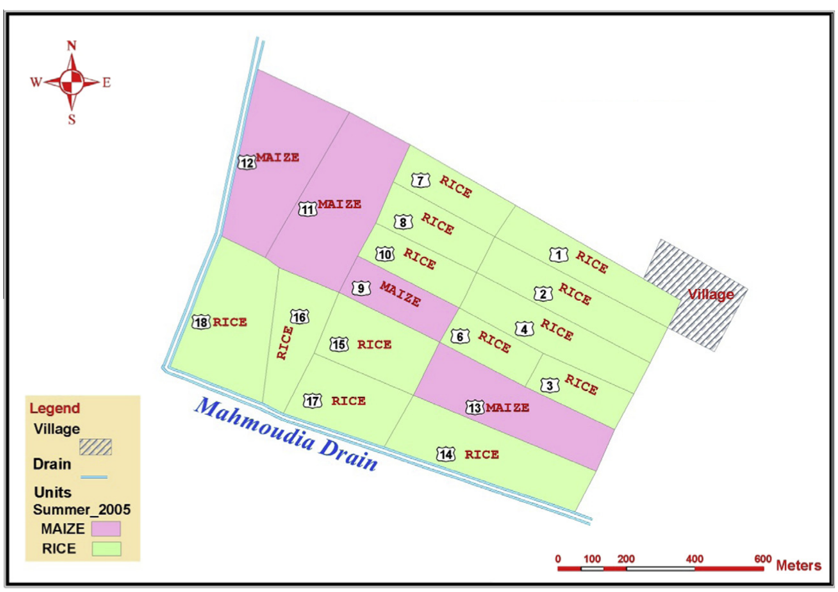

Figure 4 Crop pattern in Mashtul Pilot Area, 2005 (summer season).

Table 2 The characteristic of the different statistical criteria. No prediction capability.

RRMSE		MAE		CD	
RRMSE = 0	Model is perfect	MAE = 0	Model is perfect	CD = 0	No prediction capability
		MAE = min	Optimal	0 < CD	Some at least prediction capability
RRMSE = min	Optimal	0 < MAE	Model is less perfect	CD = max	Optimal
EF		CRM		R^2	
EF = 1	Model is perfect	CRM = 1	No prediction capability	$R^2 = 1$	Perfect
EF = max	Optimal	CRM < 1	Some at least prediction capability	$R^2 = \max$	Optimal
EF < 1	Less perfect	CRM closes to 0	Optimal	$R^2 = 0$	
EF = -∞	No prediction capability				

Table 3 Statistical performance analysers calculated between measured and simulated values for the soil moisture in the soil layers.

Crop/Layer	RRMSE	MAE	CD	EF	CRM	R^2
Wheat						
0–30 cm	0.672	1.210	0.821	0.678	−0.185	0.765
30–60 cm	0.692	1.141	0.814	0.785	−0.345	0.876
60–90 cm	0.587	0.991	0.800	0.689	−0.286	0.786
90–120 cm	0.589	0.986	0.798	0.586	−0.312	0.812
Maize						
0–30 cm	0.567	1.089	0.784	0.654	−0.294	0.812
30–60 cm	0.582	1.051	0.762	0.685	−0.265	0.804
60–90 cm	0.483	0.892	0.708	0.598	−0.210	0.764
90–120 cm	0.492	0.904	0.689	0.574	−0.298	0.798

historical measured and the simulated data. The amount of the applied irrigation was 1750 m^3 and 2350 m^3 respectively (Table 4). The high yields have been traditionally achieved by using surface irrigation. Table 4 shows water input, crop yield and water productivity in MPA maintained under two different irrigation treatments; STD and PRD in 2005. After the calibration of the Saltmed model using the STD treatment, the model was used to simulate the PRD treatment.

From Table 4 and expressing yield in terms of water productivity, the modeling results indicated that PRD is outstanding. However, as water in Egypt is given for free, it will be difficult to convince farmers to consider only the high productivity per water unit in PRD and to forget about the high productivity per feddan in case of STD PRD thus 'worked' as a deficit irrigation treatment, sustaining a similar (even higher) yield compared with conventional flood irrigation (STD), not necessarily through a change in water-use efficiency itself but possibly by 'forcing' crops to access more soil water than did crops on STD. The improvement in water productivity under the PRD treatment (Table 4) must also be viewed against this same background. The modeling results indicated that, the soil water content did increase and would have contributed to an improvement in irrigation water productivity. The dynamic changes in rootzone water content did not extend any deeper than about 80 cm. The measured and simulated crop yield in MPA trial maintained under STD and PRD irrigation treatments in 2005 are shown in Fig. 5 while, Fig. 6 shows the water productivity.

PRD irrigation method requires that both wet and dry rootzones are both simultaneously created. PRD method is a sensitive technique need very precise irrigation scheduling and good distribution uniformity is required to implement these techniques. The experiments have also shown that the dry roots are maintained in a healthy condition by water supplied to them from the wet roots [19]. This technique is capable of producing very high water productivity and improving crop quality for certain varieties. The PRD method will affect on water productivity, plant quality and nitrate leaching within the soil profile. PRD technique increases water productivity through a stress related chemical produced (ABA) by the drying roots which is then transported to the leaves. The chemical brings about physiological changes that reduce water lost from leaves through evapotranspiration. In addition to water saving, PRD has also been showed to have beneficial effects on the nutrient uptake of wheat and maize crops compared with

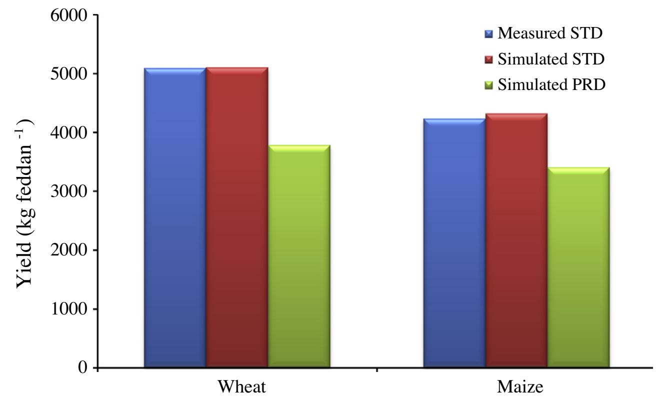

Figure 5 Measured and simulated crop yield in MPA trial maintained under STD and PRD irrigation treatments in 2005.

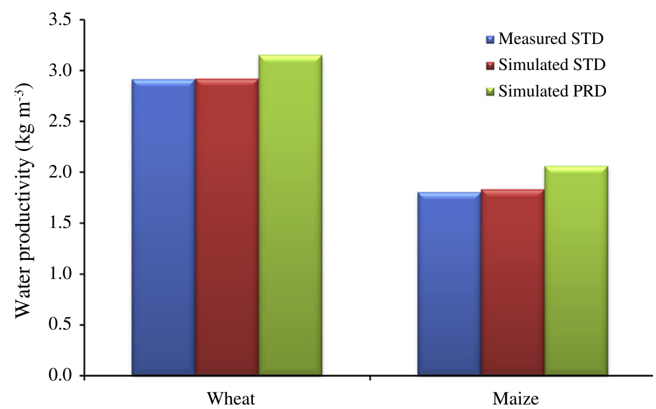

Figure 6 Measured and simulated water productivity in MPA trial maintained under STD and PRD irrigation treatments in 2005.

Table 4 Water input, crop yield and water use efficiency (MPA trial) maintained under two different irrigation treatments; STD and PRD in 2005.

	Irrigation applied (m^3 $feddan^{-1}$)		Yield (kg $feddan^{-1}$)			Yield/Irrigation applied (kg m^{-3})		
			Measured	Simulated		Measured	Simulated	
Crop	STD	PRD	STD	STD	PRD	STD	STD	PRD
Wheat	1750	1200	5088	5104	3780	2.91	2.92	3.15
Maize	2350	1650	4233	4319	3402	1.80	1.83	2.06

STD = standard flood irrigation; PRD = Partial Rootzone Drying.

STD. The modeling results of this research are summarised below:

- The PRD treatment reduced water application rates by 32% and 30% for wheat and maize respectively.
- Compared to flood irrigation, PRD treatment increased water productivity by 7% and 12% respectively and showed a reduction in crop yield by 27% and 18% respectively.

PRD may be reducing biomass production as CO_2 uptake is partly restricted due to stomatal closure causing water saving. Biomass reductions are often in the range of 10% in cereal crops [8]. However crop losses can be high if irrigation applications are not scheduled correctly. The value of benefits from water savings should be balanced with value of yield reductions and cost of implementing PRD irrigation system compared with traditional system. The irrigation system needs to be designed so that the capability of the system to discharge volumes of water matches the infiltration rate of the soil. PRD can accumulate salts in the rootzone affecting the sustainability of the land. When this occurs it is necessary to leach the salts from the rootzone. Partial root zone drying is a very useful and significant step forward in improving the water productivity of some perennial horticultural crops. While there is some risk of water stress to the plant, with careful soil water monitoring these risks can be minimised. Satisfactory implementation of deficit strategies in warm areas (areas with high levels of water evaporation), will require responsive watering systems and soils with high infiltration rates. Also, the results showed that an experimental research should be designed to the practical application and longer-term consequences of the proposed irrigation method.

6. Conclusions

In this research, a novel irrigation method was investigated, which would stimulate the endogenous stress response mechanisms of wheat and maize crops so that the water productivity is enhanced. PRD is an irrigation technique which offers a means of modifying the growth and development of crops through relatively simple changes to the method of water delivery. The technique causes the stimulation of physiological responses which are normally associated with water stress and this result in a significant reduction in water use through the production of chemical signals in drying roots. Partial drying of one half of the roots of plants is rapidly translated into a reduction in transpiration and assimilation of all the crop leaves. The value of benefits from water savings should be balanced with value of yield reductions and cost of implementing PRD irrigation system compared with traditional system. As PRD irrigation is in the research phase in Egypt further experiences are needed to evaluate economical advantages of PRD irrigation. Further research is needed to gain a better understanding of how this technique affects the distribution of soil moisture within the root zone, the development and physiology of crop growing phases on a range of soil textures and depths, percent of surface losses, percent of deep percolation losses, efficiency of using fertilizers, and overall economic cost benefit study. Finally, the research highly recommends applying the PRD method in new reclaimed areas in Egypt such as Toshka in the south valley to save water and improve crop quality.

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